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(54) **SOLID HOLLOW CORE FUEL FOR FUSION-FISSION ENGINE**

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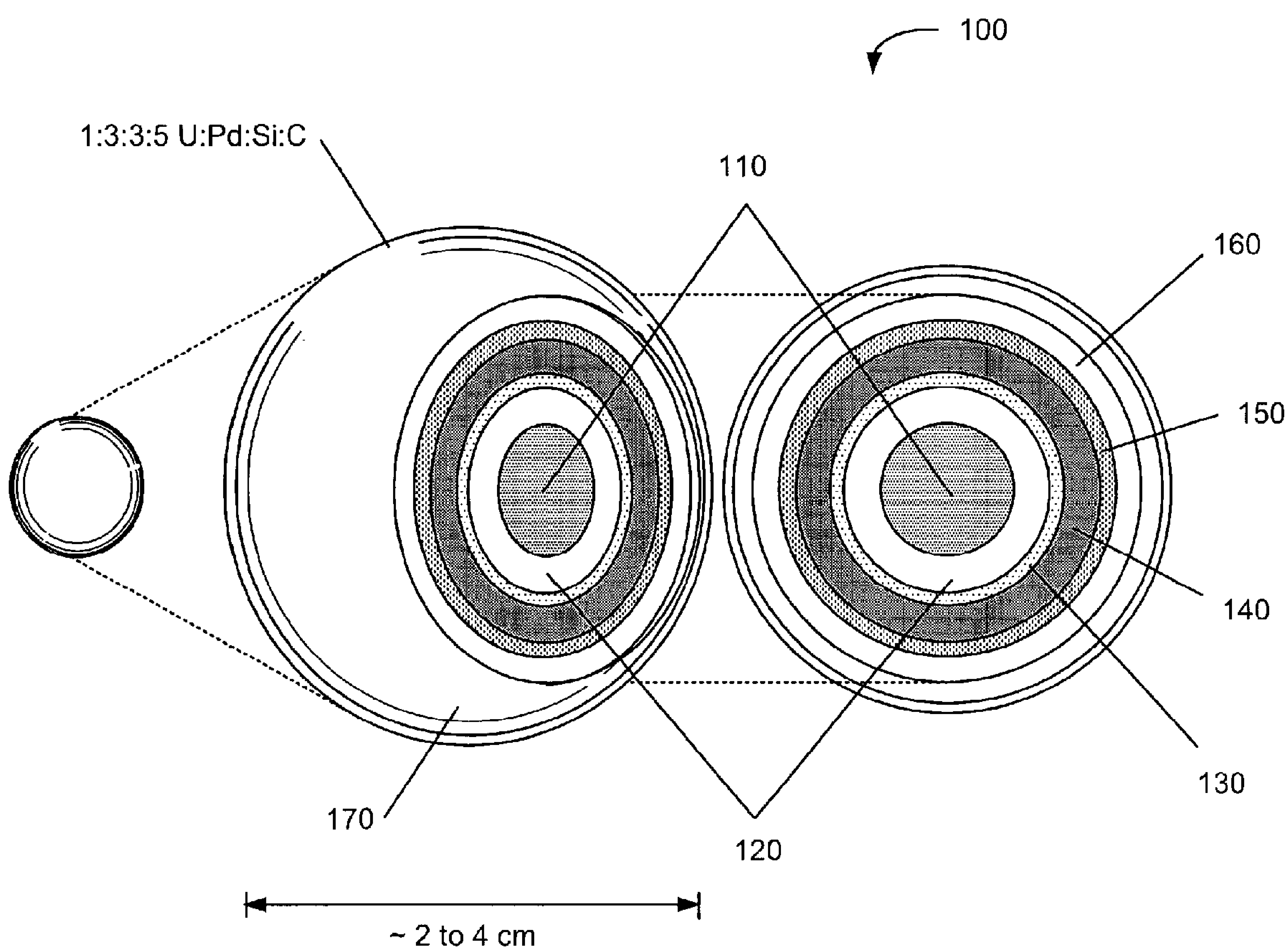
(57) **ABSTRACT**

A fuel pebble for use in a fusion-fission engine includes a buffer material and a fertile or fissile fuel shell surrounding the buffer material. The fuel pebble also includes a containment shell surrounding the fertile or fissile fuel shell. The containment shell includes silicon carbide. The fuel pebble further includes a composite material layer surrounding the containment shell and a cladding layer surrounding the composite material layer.



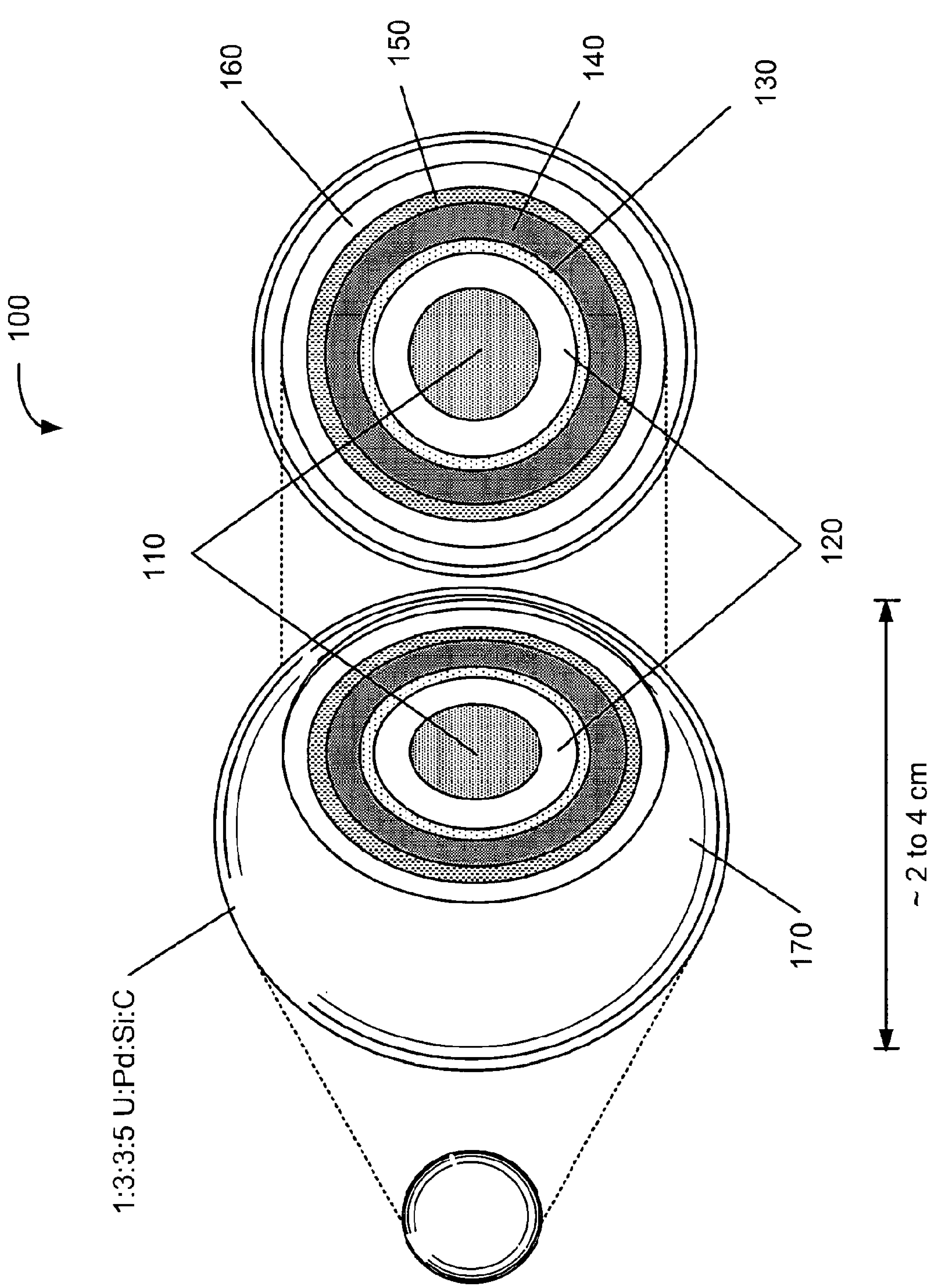
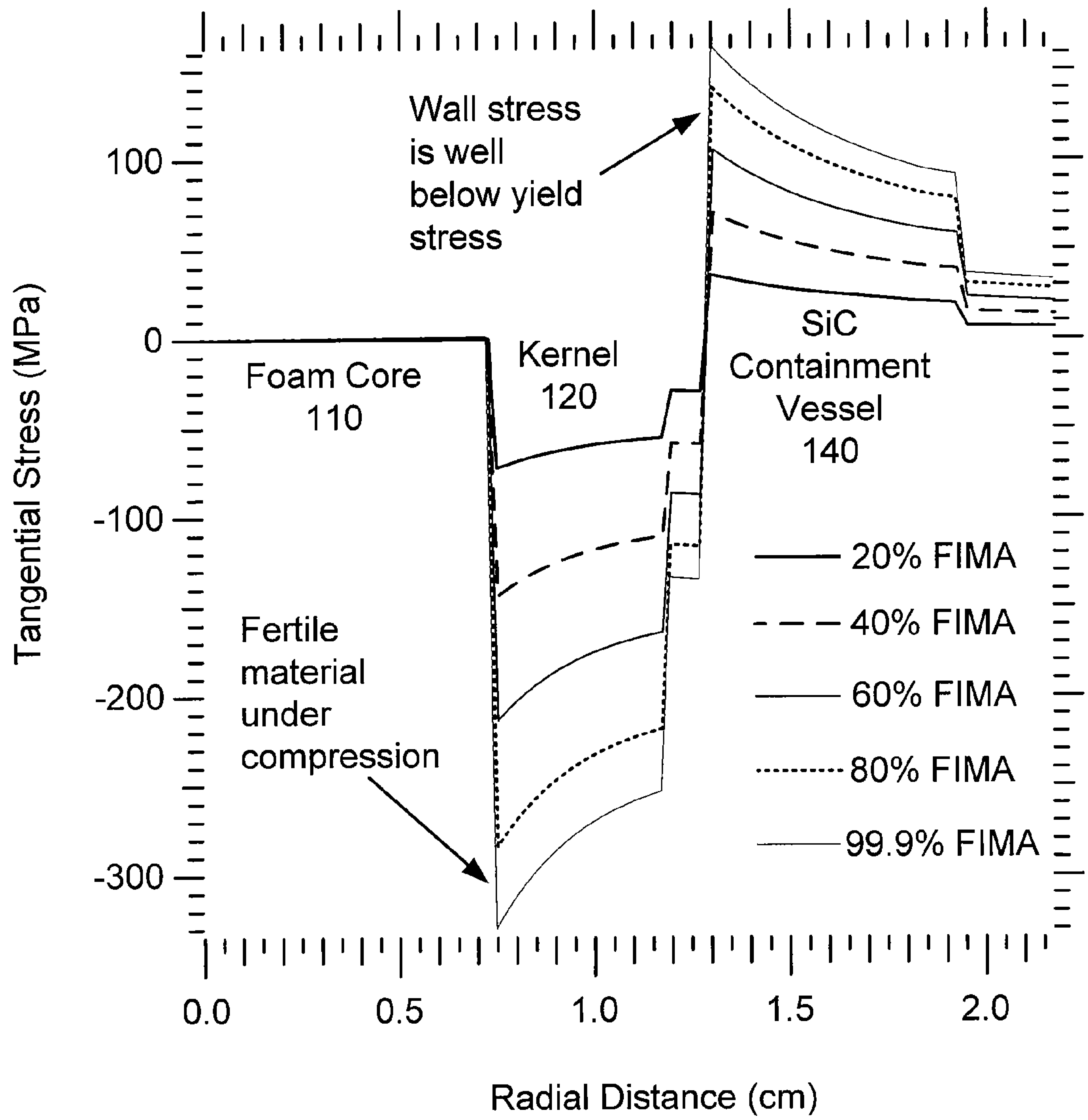


FIG. 1



Wall stress is well below yield stress
100
0
-100
-200
-300
Tangential Stress (MPa)
Foam Core 110
Kernel 120
SiC Containment Vessel 140
Fertile material under compression
20% FIMA
40% FIMA
60% FIMA
80% FIMA
99.9% FIMA
0.0
0.5
1.0
1.5
2.0
Radial Distance (cm)

FIG. 2

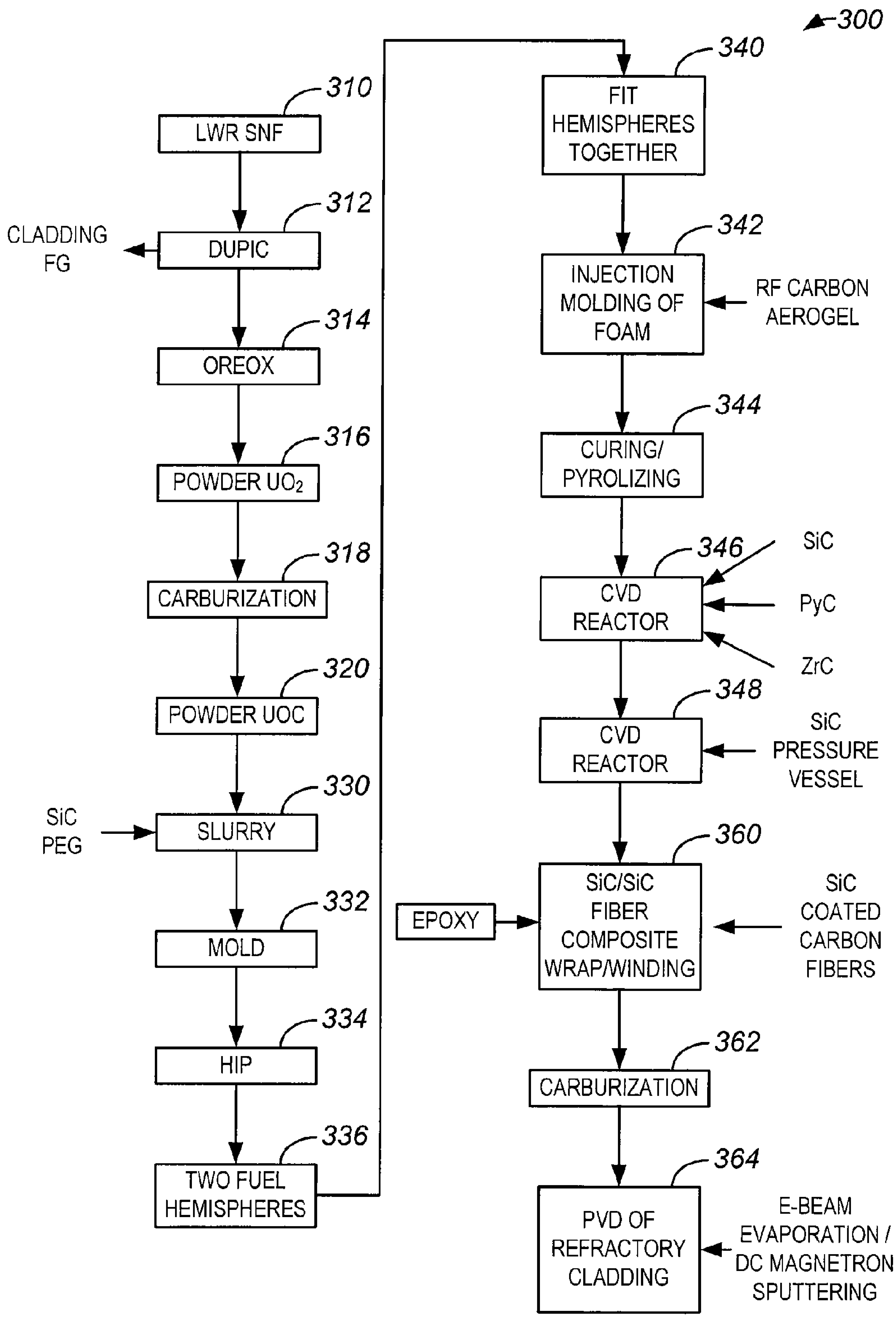

300
310
LWR SNF
312
CLADDING
FG
DUPIC
314
OREOX
316
POWDER UO_2
318
CARBURIZATION
320
POWDER UOC
330
SiC
PEG
SLURRY
332
MOLD
334
HIP
336
TWO FUEL HEMISPHERES
340
FIT HEMISPHERES TOGETHER
342
INJECTION MOLDING OF FOAM
RF CARBON AEROGEL
344
CURING/ PYROLIZING
346
CVD REACTOR
SiC
PyC
ZrC
348
CVD REACTOR
SiC PRESSURE VESSEL
360
EPOXY
SiC/SiC FIBER COMPOSITE WRAP/WINDING
SiC COATED CARBON FIBERS
362
CARBURIZATION
364
PVD OF REFRACTORY CLADDING
E-BEAM EVAPORATION / DC MAGNETRON SPUTTERING

FIG. 3

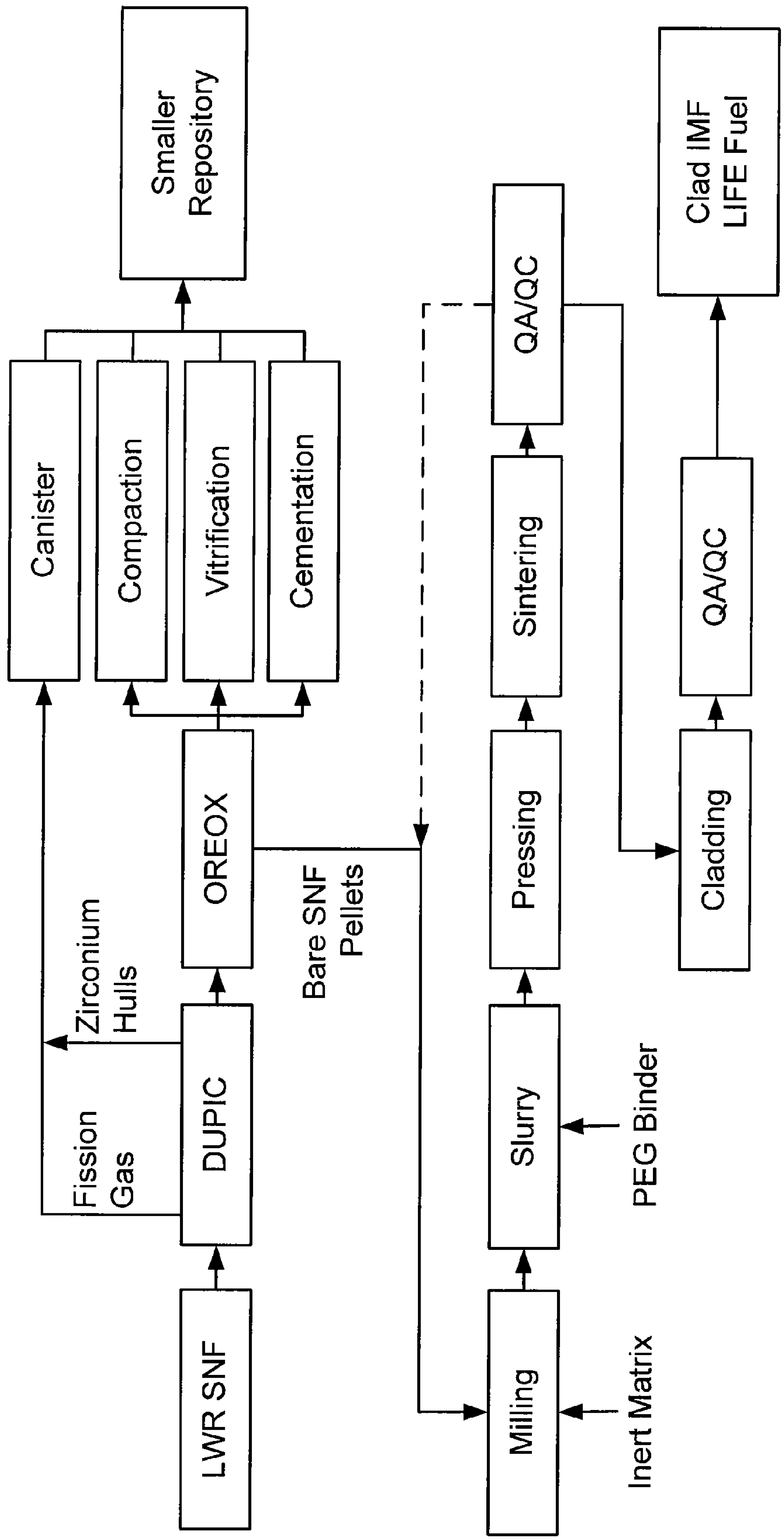

LWR SNF
DUPIC
Fission Gas
Zirconium Hulls
OREOX
Bare SNF Pellets
Canister
Compaction
Vitrification
Cementation
Smaller Repository
Milling
Inert Matrix
Slurry
PEG Binder
Pressing
Sintering
QA/QC
Cladding
QA/QC
Clad IMF LIFE Fuel

FIG. 4

SOLID HOLLOW CORE FUEL FOR FUSION-FISSION ENGINE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims benefit under 35 U.S.C. §119(e) of U.S. Provisional Patent Application No. 60/997,780, filed on Oct. 4, 2007, entitled "Hybrid Fusion-Fission Reactor," and U.S. Provisional Patent Application No. 61/130,200, filed on May 29, 2008, entitled "Hybrid Fusion-Fission Reactor Using Laser Inertial Confinement Fusion," the disclosures of which are hereby incorporated by reference in their entirety for all purposes.

STATEMENT AS TO RIGHTS TO INVENTIONS MADE UNDER FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] The United States Government has rights in this invention pursuant to Contract No. DE-AC52-07NA27344 between the United States Department of Energy and Lawrence Livermore National Security, LLC.

BACKGROUND OF THE INVENTION

[0003] Projections by the Energy Information Agency and current Intergovernmental Panel on Climate Change (IPCC) scenarios expect worldwide electric power demand to double from its current level of about 2 terawatts electrical power (TWe) to 4TWe by 2030, and could reach 8-10 TWe by 2100. They also expect that for the next 30 to 50 years, the bulk of the demand of electricity production will be provided by fossil fuels, typically coal and natural gas. Coal supplies 41% of the world's electric energy today, and is expected to supply 45% by 2030. In addition, the most recent report from the IPCC has placed the likelihood that man-made sources of CO_2 emissions into the atmosphere are having a significant effect on the climate of planet earth at 90%. "Business as usual" baseline scenarios show that CO_2 emissions could be almost two and a half times the current level by 2050. More than ever before, new technologies and alternative sources of energy are essential to meet the increasing energy demand in both the developed and the developing worlds, while attempting to stabilize and reduce the concentration of CO_2 in the atmosphere and mitigate the concomitant climate change.

[0004] Nuclear energy, a non-carbon emitting energy source, has been a key component of the world's energy production since the 1950's, and currently accounts for about 16% of the world's electricity production, a fraction that could—in principle—be increased. Several factors, however, make its long-term sustainability difficult. These concerns include the risk of proliferation of nuclear materials and technologies resulting from the nuclear fuel cycle; the generation of long-lived radioactive nuclear waste requiring burial in deep geological repositories; the current reliance on the once through, open nuclear fuel cycle; and the availability of low cost, low carbon footprint uranium ore. In the United States alone, nuclear reactors have already generated more than 55,000 metric tons (MT) of spent nuclear fuel (SNF). In the near future, we will have enough spent nuclear fuel to fill the Yucca Mountain geological waste repository to its legislated limit of 70,000 MT.

[0005] Fusion is an attractive energy option for future power generation, with two main approaches to fusion power plants now being developed. In a first approach, Inertial Confinement Fusion (ICF) uses lasers, heavy ion beams, or pulsed power to rapidly compress capsules containing a mixture of deuterium (D) and tritium (T). As the capsule radius decreases and the DT gas density and temperature increase, DT fusion reactions are initiated in a small spot in the center of the compressed capsule. These DT fusion reactions generate both alpha particles and 14.1 MeV neutrons. A fusion burn front propagates from the spot, generating significant energy gain. A second approach, Magnetic fusion energy (MFE) uses powerful magnetic fields to confine a DT plasma and to generate the conditions required to sustain a burning plasma and generate energy gain.

[0006] Important technology for ICF is being developed primarily at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL), in Livermore, Calif. There, a laser-based inertial confinement fusion project designed to achieve thermonuclear fusion ignition and burn utilizes laser energies of 1 to 1.3 MJ. Fusion yields of the order of 10 to 20 MJ are expected. Fusion yields in excess of 200 MJ are expected to be required in central hot spot fusion geometry if fusion technology, by itself, were to be used for cost effective power generation. Thus, significant technical challenges remain to achieve an economy powered by pure inertial confinement fusion energy.

SUMMARY OF THE INVENTION

[0007] According to the present invention, techniques related to fuel for a fusion-fission nuclear engine which we term Laser Inertial-confinement Fusion-fission Energy (LIFE), are provided. Such an engine is described in more detail in our commonly assigned copending U.S. patent application Ser. No. ______, entitled "Control of a Laser Inertial Confinement Fusion-Fission Power Plant," filed contemporaneously with this application, the contents of which are incorporated by reference. More particularly, an embodiment of the present invention provides an enhanced fuel pebble suitable for use in a laser inertial confinement fusion-fission power plant. Merely by way of example, the invention has been applied to the design and fabrication of a robust solid hollow core fuel pebble capable of high burn-up. The methods and systems described herein are also applicable to other nuclear power plant designs.

[0008] According to an embodiment of the present invention, a fuel pebble for use in a fusion-fission engine is provided. The fuel pebble includes a buffer material (e.g, a porous carbon aerogel) and a fertile or fissile fuel that forms a hollow shell surrounding the buffer material. The fissile fuel shell includes uranium oxy-carbide in a specific embodiment. The fuel pebble also includes a containment shell surrounding the fertile or fissile fuel shell. The containment shell includes silicon carbide (SiC). The fuel pebble further includes a composite material layer surrounding the containment shell and a cladding layer surrounding the composite material layer. The composite material layer includes a high-strength carbon fiber wrap, where the carbon fibers are coated with protective material such as silicon carbide (SiC), in a particular embodiment.

[0009] According to another embodiment of the present invention, a method of fabricating a fuel pebble for a fusion-fission engine is provided. The method includes forming a fertile or fissile shell and enclosing a buffer material inside the fertile or fissile shell. The method also includes forming a containment shell surrounding the fertile or fissile shell and wrapping the containment shell with a composite material layer. The method further includes forming a wear and corrosion-resistant cladding layer surrounding the composite material layer. The cladding also helps forms the hermetic pressure boundary for fission gas containment.

[0010] According to an alternative embodiment of the present invention, a fuel pebble for use in a fusion-fission nuclear engine is provided. The fuel pebble includes a foam core and a fertile or fissile shell surrounding the foam core. The fuel pebble also includes a containment vessel surrounding the fertile or fissile shell and a composite material layer surrounding the containment vessel. The composite material layer includes carbon fiber filaments with a protective coating. The yield stress of the composite material layer is greater than the intrinsic strength of silicon carbide (SiC), which has been measured to be approximately 450 MPa for a particular type. The fuel pebble further includes a cladding layer surrounding the composite material layer.

[0011] Numerous benefits are achieved by way of the present invention over conventional techniques. For example, the present technique provides a robust fuel for nuclear reactors that can achieve high burn-up of fertile or fissile material without failure of the fuel pebble. Additionally, embodiments of the present invention provide a fuel pebble that has a high mass fraction of fertile material. Moreover, wall stresses in fuel pebbles described herein are reduced at comparable final inventory of metal atoms burn-up levels in comparison with conventional fuels, such as tri-structural iso-tropic (TRISO) fuels. Depending upon the embodiment, one or more of these benefits may be achieved. These and other benefits will be described in more detail throughout the present specification and more particularly below.

[0012] These and other objects and features of the present invention and the manner of obtaining them will become apparent to those skilled in the art, and the invention itself will be best understood by reference to the following detailed description read in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. **1** is a simplified schematic diagram of a solid hollow core fuel pebble according to an embodiment of the present invention;

[0014] FIG. **2** is a simplified graph of stress as a function of radial distance for a solid hollow core fuel pebble according to an embodiment of the present invention;

[0015] FIG. **3** is a simplified flowchart illustrating a method of fabricating a solid hollow core fuel pebble according to an embodiment of the present invention; and

[0016] FIG. **4** is a simplified flowchart illustrating a process for generation of fertile or fissile fuel according to an embodiment of the present invention.

DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

[0017] According to the present invention, techniques related to fuel for a nuclear engine are provided. More particularly, an embodiment of the present invention provides an enhanced fuel pebble suitable for use in a laser inertial confinement fusion-fission power plant. Merely by way of example, the invention has been applied to the design and fabrication of a robust solid hollow core (SHC) fuel pebble capable of high burn-up. The methods and systems described herein are also applicable to other nuclear power plant designs. Additional discussion related to nuclear fusion-fission engines is provided in U.S. patent application Ser. No. ______, entitled "Control of a Laser Inertial Confinement Fusion-Fission Power Plant" (Attorney Docket No. 027512-000400) and U.S. patent application Ser. No. ______ (Attorney Docket No. 027512-000600US), entitled "TRISO Fuel for High Burn-Up Nuclear Engine", the disclosures of which are hereby incorporated by reference in their entirety for all purposes.

[0018] The inventors have determined that the mass fraction of fertile material in conventional compacts that include an inert material is limited by the packing efficiency of the fuel particles that make up conventional compacts. As an example, in some conventional TRISO particles, the non-fertile or fissile materials utilized to provide mechanical structure for the particle consume space that is not then available for fertile material. As a result, when the TRISO particles are compacted with inert materials to form a fuel pebble, the mass fraction of fertile material in the pebble is limited.

[0019] Additionally, the inventors have determined that in some fuel particle designs, the heat transfer from the fertile or fissile material to the coolants is limited by the inert materials disposed between the fertile or fissile material and the coolant. As an example, for coolants located at the exterior surfaces of a fuel pebble, heat from the fission reactions occurring in the fertile or fissile material must transit materials between the kernel and the coolant. For this example, the heat transfer properties are a function of particle and pebble design, limiting desirable heat transfer.

[0020] FIG. **1** is a simplified schematic diagram of a solid hollow core fuel pebble according to an embodiment of the present invention. In the embodiment illustrated in FIG. **1**, the fuel pebble **100** is referred to as a solid hollow core (SHC) pebble because the core of the pebble is preferably a porous or nano-porous foam material. The foam in the hollow core of the pebble can be formed from carbon, metals or ceramics. Referring to FIG. **1**, a buffer material **110** (e.g., a foam core) is present in the center of the fuel pebble. In a particular embodiment, as described more fully below, the buffer material includes a metal foam that is injection molded into the core of the fertile or fissile fuel shell. In some embodiments, this foam material provides a source of sacrificial silicon carbide (SiC) as well as providing regions for storage of fission gases generated in the fertile or fissile kernel **120** via chemisorption on the surface of the foam. In the embodiment illustrated in FIG. **1**, the kernel **120** is a fertile uranium oxycarbide (UOC) shell that surrounds the foam material **110**.

[0021] Because the foam core is disposed internally to the fertile shell **120** and does not surround the fertile or fissile kernel, the foam material does not result in insulation of the kernel from the coolants on the exterior of the fuel pebble. Thus, heat from the kernel produced during fission processes is transported toward the coolant without passing through the foam core. Therefore, embodiments of the present invention provide improved thermal conductivity in comparison with conventional designs because heat from the fission processes transfers outward from the kernel and the amount of insulating material through which the heat must pass is reduced.

[0022] In an embodiment, the foam material is fabricated from a porous carbon core that provides an expansion volume for fission gases. In addition to this porous carbon or other foam material, the core can include a sacrificial silicon carbide (SiC) material. For example, the sacrificial silicon carbide (SiC) can react with palladium produced as a fission byproduct to form Pd_5Si. The consumption of the palladium in the core prevents the palladium from reacting with and thereby degrading the silicon carbide (SiC) containment vessel, described more fully below. Additionally, the use of sacrificial silicon carbide (SiC) in the core should mitigate attack of the fuel materials by fission products. One or more pyrolytic carbon layers can be included as part of the core **110** and may serve as transition layers between the buffer material and the fertile or fissile shell, described more fully below.

[0023] The solid hollow core fuel pebble also includes a fertile or fertile or fissile shell **120** surrounding the foam core. The fertile or fissile shell can include a variety of materials such as metallic uranium, uranium dioxide (UO_2), uranium carbide, uranium oxy-carbide (UOC), uranium nitride, and various other forms of uranium; metallic plutonium, plutonium dioxide (PuO_2), plutonium carbide, plutonium oxy-carbide (PuOC), plutonium nitride, and other various forms of plutonium; and various forms of thorium, or the like. The fuel materials can originate from weapons grade plutonium, highly enriched uranium, light water reactor spent nuclear fuels, depleted uranium, natural uranium, natural thorium ore, or the like.

[0024] At the interface of the foam core and the fertile shell, it is possible to form 1:3:3:5 U:Pd:Si:C as a result of the reaction of palladium and uranium from the fertile or fissile shell and silicon carbide (SiC) in the foam core. 1:3:3:5 U:Pd:Si:C, which has a melting point of ~1952° C., can serve to remove fission products, namely palladium, and is very stable. Other high-melting refractory compounds may also form during the reaction of this, or any other sacrificial material.

[0025] Surrounding the fertile shell is a multi-purpose layer or series of layers **130** containing one or more of the following materials: silicon carbide (SiC), zirconium carbide, and/or pyrolytic carbon. The silicon carbide (SiC) will provide sacrificial material that will react with fission products such as palladium. The use of sacrificial materials including silicon carbide (SiC) is discussed above. The zirconium carbide layer provides a diffusion barrier that reduces or prevents direct contact of fission products from the fertile or fissile kernel with the silicon carbide (SiC) containment shell **140**. Additionally, ZrC can serve as an oxygen getter to reduce the oxygen pressure due to the generation of free oxygen from, for example, UOC. The pyrolytic carbon layer positioned between the hollow kernel and the silicon carbide (SiC) containment shell, can serve as a transition layer from the kernel to the SiC shell, as described more fully below. The transition layer provides interfacial benefits that prolong the fuel pebble's utility and lifetime.

[0026] The silicon carbide (SiC) sacrificial material, the zirconium carbide diffusion barrier, and/or the pyrolytic carbon transition layer are formed, either as sequential single layers or as a multi-layer stack in which each of the layers, which may be referred to as sub-layers, is deposited one or more times in a periodic or non-periodic manner. Thus, for example, several layers of the zirconium carbide diffusion barrier may be deposited in conjunction with the other sub-layers to form the multipurpose "layer" **130**.

[0027] The silicon carbide (SiC) containment vessel **140** is an annular shell surrounding the interior layers and makes up a portion of a pressure vessel or structure that serves to contain the fission gases within the fuel pebble. In the design of the solid hollow core fuel pebble described herein, the silicon carbide (SiC) containment vessel **140** does not have to bear all the pressure resulting from the fission gases because the additional layers surrounding the silicon carbide (SiC) shell also contribute to the containment of the fission gases. Thus, embodiments of the present invention differ from some conventional designs utilizing only a single silicon carbide (SiC) layer to contain the fission gas pressure. As described below, the series of layers illustrated in FIG. **1** provide either increased strength for the fuel pebble or a similar strength while utilizing less materials. By utilizing a reduced amount of inert materials, the mass fraction of fertile or fissile material is thereby increased as desired.

[0028] A layer of high-strength carbon fiber windings **150**, where the fibers are coated with a protective material such as silicon carbide (SiC), is illustrated in FIG. **1**. Other protective coating materials are possible, including but not limited to zirconium carbide (ZrC). In some embodiments, layer **150** is referred to as a carbon fiber wrap. As will be evident to one of skill in the art, carbon fiber materials, also referred to as composite materials, are characterized by failure strengths measured in the GPa range. Thus, in some embodiments, the use of a SiC/SiC fiber wrap provides an increase in strength of up to or over a factor of five in comparison with the strength of the SiC containment vessel.

[0029] As illustrated in FIG. **1**, in order to increase the strength of the fission gas containment vessel structure, the silicon carbide (SiC) containment shell **140** is wrapped using carbon fiber. The carbon fiber, typically in a string-like or filament form, is wound around shell **140** in a particular embodiment to form a carbon fiber wound spherical pressure vessel. Epoxies, resins, or other appropriate materials are utilized in forming the carbon fiber windings. As will be evident to one of skill in the art, techniques applicable to the fabrication of carbon filament wound pressure vessels such as self-contained breathing apparatuses used by firefighters and other emergency personnel, SCUBA tanks for divers, oxygen cylinders for medical and aircraft uses, fuel storage for alternative fuel vehicles, and the like, will also be applicable to embodiments of the present invention. One of ordinary skill in the art would recognize many variations, modifications, and alternatives.

[0030] The size the partially fabricated fuel pebble at the fiber wrap shell is suitable for the application of a number of carbon fiber composite wrapping techniques. Thus, the relatively large size (~2 to 4 cm) of the fuel pebble allows for the use of a silicon carbide (SiC) wrap that results in a very strong pressure vessel. Similar techniques may not be applicable or suitable for smaller dimension fuels. In one wrapping technique, the spherical pebble is continuously and rotated on a turn-table, while the silicon-carbide coated carbon has binder applied to its surface, and is continuously fed to the rotating pebble.

[0031] The high strength composite wrapped shell **150** is surrounded by a transition layer **160** that provides a smooth surface in comparison with the fiber wrap layer, which will generally have variations due to the filament size used during the wrapping process. A variety of materials can be utilized in forming the fiber-to-clad transition layer **160**, including: graphite silicon carbide (SiC), zirconium, zirconium carbide (ZrC), refractory metals, refractory metal carbides, ferritic steels, or the like. These materials can be applied as single layers, or as multi-layer structures.

[0032] The fuel pebble includes a corrosion resistant cladding layer **170** made of a material that is compatible with molten salt coolants, which include but are not limited to refractory metals such as tungsten and vanadium. Molten salt coolants, including FLIBE ($2LiF+BeF_2=Li_2BeF_4$ and FLINABE ($LiNaBeF_4$), can attack the fuel pebble, reducing useful lifetime of the pebble. Therefore, the cladding layer material is characterized by a resistance to attack from the molten salt coolant(s) utilized to remove heat from the fuel pebble. Additionally, tritium fluoride, which behaves like hydrofluoric acid, is formed in the molten salt coolant as a result neutron bombardment and the consequent transmutation of lithium that comprises the salt. Therefore, the cladding layer **170** is also selected to be resistant to attack by hydrofluoric acid. Accordingly, embodiments of the present invention utilize cladding layers including refractory metals such as tungsten and vanadium, refractory-metal carbides, or the like.

[0033] FIG. **2** is a simplified graph of stress as a function of radial distance for a solid hollow core (SHC) fuel pebble according to an embodiment of the present invention. As illustrated in FIG. **2**, the tangential stress is plotted as a function of radial distance, starting in the center of the foam core **110**, passing through the hollow fertile or fissile kernel **120**, the multipurpose layer **130** (not marked in the figure for purposes of clarity, the silicon carbide (SiC) containment vessel **140**, and the outer layers including the composite wrap and cladding layers. The tangential stress is plotted as a function of the burn-up measured in percent Fissions per Initial Metal Atom (FIMA). As shown in FIG. **2**, the foam core experiences a minimal amount of stress, either compressive or tensile, during the entire burn-up cycle. The hollow kernel **120** experiences increasing compressive stress as the burn-up cycle progresses, eventually reaching a level of greater than −300 MPa at the foam-core/fuel-kernel interface at 99.9% FIMA. As the hollow kernel begins to fracture at very high levels of burn-up, this compressive stress serves to hold the curved pieces of the fractured kernel together, thereby preventing the fuel pebble from failing.

[0034] The silicon carbide (SiC) containment vessel **140** is under increasing tensile stress as the burn-up cycle proceeds to full (e.g., 99.9%) burn-up. Although the wall stress increases to approximately 150 MPa as a result of radioactive fission gases such as krypton-85 generated in the fertile or fissile kernel, the wall stress is well below the yield stress of SiC, which in some cases is approximately 450 MPa. As illustrated, the stresses in the composite wrap layer are even lower than in the SiC containment vessel layer, and are far below the yield stresses of such composite layers, which can be in GPa range. Thus, the fuel pebble described herein provides for containment of fission gases without pebble failure throughout the entire burn-up cycle, i.e., 99.9% FIMA.

[0035] FIG. **3** is a simplified flowchart illustrating a method of fabricating a solid hollow core fuel pebble according to an embodiment of the present invention. In the embodiment illustrated in FIG. **3**, the fertile or fissile fuel is recycled from light water reactor (LWR) spent nuclear fuel (SNF) **310**. The LWR SNF is processed using the DUPIC (Direct Use of spent PWR fuel in CANDU reactors) process **312**, in which the cladding from the fuel rods and the fission gases are removed. An OREOX (Oxidation, REduction of enriched OXide fuel) process **314** is then used to produce a powder form of uranium dioxide (UO_2) **316**. A carburization process **318** is then used to generate a powdered form of uranium oxy-carbide (UOC) **320**. It should be noted that although UOC is utilized as the fertile or fissile kernel in some embodiments, this is not required by the present invention. In other embodiments, other fertile or fissile materials are utilized depending on the particular application. Thus, although a process to generate UOC from LWR SNF is illustrated in steps **310-320**, this particular fuel process is not required and other fuels can be generated and utilized in the solid hollow core fuel pebble described herein. Accordingly, other fertile or fissile materials including weapons-grade plutonium (WG-Pu), natural and depleted uranium (DU), highly enriched uranium (HEU), and the like can be utilized in forming the fertile or fissile kernel used in various embodiments. One of ordinary skill in the art would recognize many variations, modifications, and alternatives.

[0036] FIG. **4** is a simplified flowchart illustrating a process for generation of fertile or fissile fuel according to an embodiment of the present invention. It is likely that the most logical solid fuel option would leverage as much of the DUPIC fuel cycle as possible, as illustrated in FIG. **4**. As described in the literature, the key process of the DUPIC fuel cycle is the oxidation and reduction of PWR spent oxide fuel (known as OREOX) to prepare powder for CANDU fuel fabrication. This is a completely dry process without any separation of fertile or fissile isotopes from the spent PWR fuel. It is assumed that the composition of PWR spent oxide fuel fed to the OREOX process consists of U, Pu, Np, Am, Cm and miscellaneous fission products. The composition of the powder leaving the OREOX process for fabrication of the CANDU fuel consists of U, Pu, Np, Am, Cm and miscellaneous fission products. This is also the composition of dry powder available from PWR SNF for fabrication of fuel as described herein.

[0037] The primary waste stream coming from the DUPIC fuel fabrication process consists of metallic components from spent PWR fuel, fission gases, and semi-volatile fission products released from the fuel during treatment. Noble gases such as Kr and Xe are compressed in 50-liter cylinders for long-term storage and decay. Tritium and carbon are trapped on molecular sieves and barium hydroxide, respectively. These are then mixed with cement, which is poured into large drums for disposal. The discarded cladding (hulls) are also mixed with -cement for disposal. Radioactive iodine is trapped on a silver zeolite and Cs and Ru are fixed on filters and vitrified for disposal. As described in relation to FIG. **3**, the inventors have developed computational models for solid hollow core fuel that account (to the extent possible) for the effects of fuel irradiation on materials stress and failure. The inventors have determined that for the solid hollow core fuel pebbles described herein, the stresses, due to fission gas accumulation, thermal gradients, and irradiation-induced swelling of the materials can be maintained below levels that would result in failure of the primary silicon-carbide (SiC) pressure vessel or boundary **140** illustrated in FIG. **1**.

[0038] Referring once again to FIG. **3**, a slurry is formed **330**, typically utilizing a mixture of silicon carbide (SiC), polyethylene glycol (PEG), or other binder, and fertile or fissile powder. The slurry is placed into a mold **332** and a hot isostatic pressing (HIP) **334** process is utilized to form two hemispherical shells **336** of fuel that have hollow central regions. Isotropic compression may be achieved hydrostatically, with the slurry contained within a flexible membrane. As will be appreciated with reference to FIG. **1**, the fuel kernel shell will be fabricated in subsequent processing steps by joining the two hemispherical sections together with the hollow core between the sections.

[0039] In order to form the fuel shell, the two hemispherical sections are fit together 340 and an injection molding process is used to form the foam material at the center of the solid hollow core fuel pebble. As an example, a resorcinol-formaldehyde (RF) or other solution can be injected into the center of the hollow fertile or fissile fuel kernel, thereby enabling in situ formation of a carbon aerogel during heating and consequent pyrolysis 344, Small holes in the hollow kernel enable the release of pyrolysis gas from the hollow core. The carbon aerogel could also be placed in the hollow core by other injection molding processes. After filling the hollow core of the kernel with carbon foam, the resulting part is known as a foam-core/fuel-kernel combination. Although the embodiment described above forms the fuel shell and then injects the buffer material into the fuel shell, this is not required by embodiments of the present invention. In other process flow, the buffer material is formed and the fuel shell is then positioned to surround the buffer material. One of ordinary skill in the art would recognize many variations, modifications, and alternatives. For example, the carbon aerogel foam could be formed in the two kernel hemispheres before assembly into SHC kernel.

[0040] In order to form the multipurpose layer 130, the foam-core/fuel-kernel combination is placed into a chemical vapor deposition (CVD) reactor 346 in which one or more layers are deposited. The CVD reactor may utilize a reduced or atmospheric pressure, plasma enhancement, or the like.

[0041] The silicon carbide (SiC) sacrificial material, the zirconium carbide diffusion barrier, and/or the pyrolytic carbon transition layer are formed, either as sequential single layers or as a multi-layer stack in which each of the layers, which may be referred to as sub-layers, is deposited one or more times in a periodic or non-periodic manner. Thus, for example, several layers of the zirconium carbide diffusion barrier may be deposited in conjunction with the other sub-layers to form the multipurpose "layer."

[0042] Either the same or a different CVD reactor is utilized 348 to form the primary silicon carbide (SiC) containment shell, or pressure boundary 140. In some embodiments, the interfaces between various layers of the structure are not exposed to an ambient environment during the CVD process, improving the fuel performance. Thus, in some embodiments, a single CVD reactor is utilized with multiple gas sources. In other embodiments, multiple CVD reactors joined by a load-lock vacuum interface can be utilized to achieve results similar to those achieved with a single reactor. The high-strength carbon fiber composite wrap or winding process 360 is then utilized to form the composite wrap layer 150. In an embodiment, high-strength carbon fibers or filaments, coated with a protective material such as silicon carbide (SiC), are utilized to form the wound pressure vessel. Other protective coating materials can also be used on the surface of the fibers.

[0043] After the winding process, a carburization process 362 is utilized, followed by formation of the cladding 364, typically using refractory metals. As illustrated in FIG. 3, a physical vapor deposition (PVD) process is utilized to deposit refractory metals such as tungsten or vanadium. Various PVD processes including electron-beam evaporation, DC magnetron sputtering, or the like can be utilized depending on the particular materials to be deposited. One of ordinary skill in the art would recognize many variations, modifications, and alternatives. For example, the spherical cladding can be formed from two pre-existing free-standing hemispherical shells.

[0044] It should be appreciated that the specific steps illustrated in FIG. 3 provide a particular method of fabricating a solid hollow core fuel pebble according to an embodiment of the present invention. Other sequences of steps may also be performed according to alternative embodiments. For example, alternative embodiments of the present invention may perform the steps outlined above in a different order. Moreover, the individual steps illustrated in FIG. 3 may include multiple sub-steps that may be performed in various sequences as appropriate to the individual step. Furthermore, additional steps may be added or removed depending on the particular applications. One of ordinary skill in the art would recognize many variations, modifications, and alternatives.

[0045] For example, one variation is that the fuel pebbles can be filled with powders of fertile or fissile materials, including, but not limited to: uranium, thorium, plutonium; oxides of uranium, thorium, and plutonium; carbides of uranium, thorium, and plutonium; oxy-carbides of uranium, thorium, and plutonium; nitrides of uranium, thorium and plutonium; and other chemical forms of uranium, thorium and plutonium. In such implementations vibration can be used during filling to maximize the packing density of particles within the hollow pressure boundary. This embodiment has the advantage of eliminating the need for fertile or fissile particle consolidation, and hot isostatic pressing. In addition, thermally-conductive carbon, metallic or ceramic powders can be added to fill the interstitial spaces between the fertile or fissile material powders, thereby enabling improved thermal conductivity and relatively high rates of heat transfer. These thermally-conductive powders have a particle-size distribution typically smaller than that of the fertile or fissile material powders, and can be selected to enable in situ sintering of the fuels during a "fuel formation" or "fuel burn-in phase." Vibration can be used during filling to maximize the packing density of particles within the hollow pressure boundary.

[0046] It is also understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application and scope of the appended claims.

1. A fuel pebble comprising:

a buffer material;

a fissile fuel shell surrounding the buffer material;

a containment shell comprising silicon carbide surrounding the fissile fuel shell;

a composite material layer surrounding the containment shell; and

a cladding layer surrounding the composite material layer.

2. The fuel pebble of claim 1 wherein the buffer material comprises a porous carbon material.

3. The fuel pebble of claim 2 wherein the buffer material further comprises at least one of a silicon carbide material or a pyrolytic carbon material.

4. The fuel pebble of claim 1 wherein the fissile fuel shell comprises a uranium oxy-carbide material.

5. The fuel pebble of claim 1 further comprising a diffusion barrier surrounding the fissile fuel shell.

6. The fuel pebble of claim 5 wherein the diffusion barrier comprises a zirconium carbide material.

7. The fuel pebble of claim **6** wherein the diffusion barrier further comprises at least one of a silicon carbide material or a pyrolytic carbon material.

8. The fuel pebble of claim **1** wherein the composite material layer comprises a carbon fiber layer.

9. The fuel pebble of claim **1** wherein the cladding layer comprises at least one of a refractory metal or a metal carbide material.

10. A method of fabricating a fuel pebble comprising:

forming a fissile shell;

enclosing a buffer material inside the fissile shell;

forming a containment shell surrounding the fissile shell;

wrapping the containment shell with a composite material layer; and

forming a cladding layer surrounding the composite material layer.

11. The method of claim **10** wherein enclosing the buffer material inside the fissile shell comprises injection molding a foam material.

12. The method of claim **11** wherein the foam material comprises a carbon aerogel material.

13. The method of claim **10** wherein the buffer material further comprises a sacrificial silicon carbide material.

14. The method of claim **10** further comprising forming at least one of a sacrificial layer, a diffusion barrier, or a transition layer surrounding the fissile shell at a position interior to the containment shell.

15. The method of claim **10** wherein forming the containment shell comprises depositing silicon carbide using a chemical vapor deposition process.

16. The method of claim **10** wherein the composite material layer comprises carbon fibers coated with silicon carbide.

17-18. (canceled)

19. The method of claim **16** wherein a yield stress of the composite material layer exceeds 450 MPa.

20. The method of claim **10** wherein forming the cladding layer comprises depositing the cladding layer using a physical vapor deposition process.

21. The method of claim **18** wherein the cladding layer comprises a refractory metal.

22. (canceled)

23. A fuel pebble comprising:

a foam core;

a fissile shell surrounding the foam core;

a containment vessel surrounding the fissile shell;

a composite material layer surrounding the containment vessel and comprising carbon fiber filaments, wherein a yield stress of the composite material layer is greater than 450 MPa; and

a cladding layer surrounding the composite material layer.

24. The fuel pebble of claim **23** further comprising a zirconium carbide diffusion barrier disposed between the fissile shell and the containment vessel.

25. The fuel pebble of claim **23** wherein the foam core comprises an RF carbon aerogel.

26. The fuel pebble of claim **23** wherein the fissile shell comprises uranium oxy-carbide.

27. (canceled)

28. The fuel pebble of claim **23** wherein the fuel pebble is characterized by a mass fraction of fissile material greater than 10%.

29-32. (canceled)

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